Gait & Posture 30 (2009) 265–269

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Runner Up of the ESMAC 2008 Best Paper Award

The Gait Profile Score and Movement Analysis Profile

Richard Baker [a,b,c,d], Jennifer L. McGinley [a,c,*], Michael H. Schwartz [e,f,g], Sarah Beynon [a], Adam Rozumalski [e,g], H. Kerr Graham [a,h], Oren Tirosh [a]

[a] Murdoch Childrens Research Institute, Royal Children's Hospital, Melbourne, Australia
[b] Department of Mechanical and Manufacturing Engineering, The University of Melbourne, Australia
[c] School of Physiotherapy, The University of Melbourne, Australia
[d] School of Physiotherapy and National Centre for Prosthetics and Orthotics, La Trobe University, Australia
[e] Gillette Children's Speciality Healthcare, St Paul, MN, USA
[f] Department of Orthopaedic Surgery, University of Minnesota, USA
[g] Department of Biomedical Engineering, University of Minnesota, USA
[h] Department of Orthopaedics, The Royal Children's Hospital, Melbourne, Australia

This paper was selected by an ESMAC Reading Committee headed by Professor Maria Grazia Benedetti. The present paper was edited by Dr. Tim Theologis.

ARTICLE INFO

Article history:
Received 15 March 2009
Received in revised form 28 April 2009
Accepted 18 May 2009

Keywords:
Gait pathology
Outcome
Gait Profile Score
Gait Deviation Index
Movement Analysis Profile

ABSTRACT

The Gait Deviation Index (GDI) has been proposed as an index of overall gait pathology. This study proposes an interpretation of the difference measure upon which the GDI is based, which naturally leads to the definition of a similar index, the Gait Profile Score (GPS). The GPS can be calculated independently of the feature analysis upon which the GDI is based. Understanding what the underlying difference measure represents also suggests that reporting a raw score, as the GPS does, may have advantages over the logarithmic transformation and z-scaling incorporated in the GDI. It also leads to the concept of a Movement Analysis Profile (MAP) to summarise much of the information contained within kinematic data.

A validation study on all children attending a paediatric gait analysis service over 3 years (407 children) provides evidence to support the use of the GPS through analysis of its frequency distribution across different Gross Motor Function Classification System (GMFCS) and Gillette Functional Assessment Questionnaire (FAQ) categories, investigation of intra-session variability, and correlation with the square root of GGI. Correlation with GDI confirms the strong relationship between the two measures.

The study concludes that GDI and GPS are alternative and closely related measures. The GDI has prior art and is particularly useful in applications arising out of feature analysis such as cluster analysis or subject matching. The GPS will be easier to calculate for new models where a large reference dataset is not available and in association with applications using the MAP.

1. Introduction

Instrumented three-dimensional gait analysis generates kinematic measurements of a wide range of variables across the gait cycle. These span different joints and different planes. Clinical decisions are generally based on an interpretation of the complex information contained in these highly interdependent data. It can often be useful, however, to have a single measure of the 'quality' of a particular gait pattern. Such a measure can quantify the overall severity of a condition affecting walking, monitor progress, or evaluate the outcome of an intervention prescribed to improve the gait pattern.

Although other measures have been proposed, the only one to have widespread clinical acceptance is the Gillette Gait Index [1] (GGI, originally referred to as the Normalcy Index), which quantifies the difference between data from one gait cycle for a particular individual and the average of a reference dataset from people exhibiting no gait pathology. The GGI, however, has several shortcomings. These have been well documented and largely overcome in a recent paper proposing an alternative, the Gait Deviation Index [2] (GDI). The GGI incorporates temporal spatial as well as kinematic parameters. The GDI uses only kinematic variables, and might thus be taken as a cleaner reflection of gait quality. The entire variability in kinematic variables across the gait cycle is used, rather than a small number of discrete parameters, thereby removing much of the subjectivity in choosing those parameters. Selection of the parameters for the GGI was specific to children with cerebral palsy whereas the GDI would appear to be a more general measure of gait pathology.

* Corresponding author at: Murdoch Childrens Research Institute, Hugh Williamson Gait Laboratory, Flemington Road, Parkville, Victoria 3052, Australia.
E-mail address: jennifer.mcginley@mcri.edu.au (J.L. McGinley).

0966-6362/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.gaitpost.2009.05.020

It has been shown that the GGI requires a reasonably large number of people in the reference dataset [3], and that values can vary significantly between different reference datasets [4]. In contrast, values of the GDI appear much less sensitive to differences in the reference data [5]. The GDI proceeds naturally from the gait feature analysis, which provides considerable data compression and provides a framework for other analytical techniques such as cluster analysis for gait classification [6]. Finally, the GDI has been demonstrated to correlate well with GGI and the Functional Assessment Questionnaire (FAQ) in a comprehensive validation study [2].

As with any other measure, the GDI does have some limitations. The technique depends on the preliminary analysis of a large dataset containing examples of all likely gait deviations (3351 subjects were used in the original study [2]). Although the authors have made the gait features derived from this analysis available for use, this does limit the potential for this technique to be expanded to other applications. Deriving a similar index for a new biomechanical model based on a different marker set, incorporating functional calibration, or including more complex modelling of the foot, for example, would be a considerable undertaking.

The GDI is a scaled version of the Euclidean distance of a subject's kinematics from the average of a reference dataset calculated in a basis comprised of 15 gait features. At first sight this appears a somewhat abstract quantity and the clinical interpretation of the measure is based upon its scaling relative to the reference dataset. That scaling has been chosen to ensure a measure with good statistical properties.

This paper proposes a simpler interpretation of the distance measure underlying the GDI, which leads to the proposal of a modified measure that can be calculated independently of the feature analysis. This adds to our understanding of how it can be interpreted clinically, and suggests that there may be advantages in using a raw score (as opposed to a scaled index). The paper thus presents data to validate such a raw score, and uses the new understanding of the distance measure as a basis for considering the relative advantages and disadvantages of raw scores or scaled indices.

2. Method

2.1. Interpreting the difference measure of the GDI

The key to understand the difference measure used in the GDI is to recognise that the feature analysis is based on projecting the original gait data onto the gait features using an orthonormal transformation. By definition, the Euclidean distance – and therefore the RMS difference – between any two gait vectors will be preserved by any such transformation. Thus, if all 459 gait features were used in the GDI (rather than just the first 15), the difference measure used in the GDI would be the *RMS difference between the patient's data and the average from the reference dataset taken over all relevant kinematic variables, for the entire gait cycle*. For reasons which will emerge below, this quantity will be referred to as the Gait Profile Score (GPS). As only the first 15 features are used in the GDI (because this represents a close approximation to the original gait data), the actual distance measure will be a close approximation to the GPS. A more formal proof of this is attached as an electronic appendix.

2.2. Definition of Gait Variable Scores (GVS), the Movement Analysis Profile (MAP) and the Gait Profile Score (GPS)

Appreciating that the fundamental quantity on which the GDI is based is the RMS difference between the gait vector and the average gait vector for people with no gait pathology suggests that there may be value in considering the RMS difference between a similar quantity calculated for a single gait variable rather than the entire gait vector. This will be referred to as a Gait Variable Score (GVS). The GVS for nine key relevant kinematic variables for the right and left legs can be combined to form a Movement Analysis Profile (MAP, Fig. 1). The RMS average of all the variable scores for a particular side will then equal the GPS calculated from the entire gait vector. It is also possible to calculate an overall GPS from the variable scores from both sides. Given that the pelvis is common to both segments it is sensible to include pelvic kinematics from one side only (the left is used by convention in this paper).

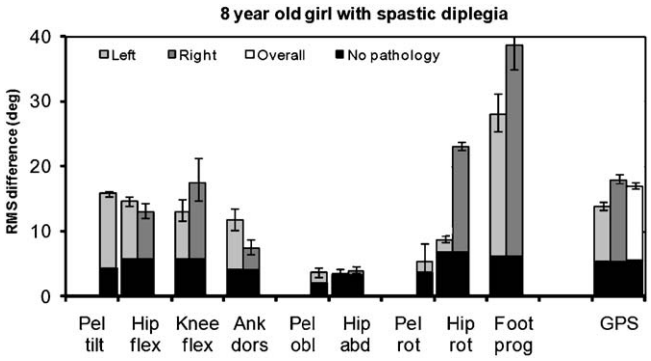

Fig. 1. The Movement Analysis Profile. Each column corresponds to one of the kinematic variables. Its height represents the (RMS) average difference across time between a specific gait cycle and the average gait cycle from people with no gait pathology. The black area at the foot of the columns represents the average value of this for people with no gait pathology. The GPS for left side, right side and overall gait pattern are displayed in the rightmost column.

2.3. Validation of the Gait Profile Score

The GPS already has high face validity. The formal validation focuses on its statistical properties, how it is distributed, its intra-session reliability, and its concurrent validity compared to the FAQ, Gross Motor Function Classification System (GMFCS), GDI, and GGI. The data upon which this is based came from all patients under the age of 18 attending for an instrumented gait analysis at a tertiary paediatric hospital during the years 2005–2007. If patients attended more than once during this period, then only data from their first visit were included. Data from a sample of convenience of 38 children under 18 years of age with no known gait pathology were used to form the reference dataset.

All data had been captured using a VICON 512 or MX system and processed with the PluginGait component for Workstation software (Vicon, Oxford, UK) based on the required marker set with the use of knee alignment devices during a static trial. Two AMTI force plates were used to capture force plate data. Trials were processed sequentially. If valid force plate data were available then the first three left and right gait cycles identified as having valid kinematic and kinetic data for each patient were included in the analysis (although no reference was made to kinetic data in this particular study). If valid force plate data was not available then the first three left and right gait cycles identified as having valid kinematic data for each patient were included. Data was uploaded into Gaitabase (http://gaitabase.rch.org.au) which includes modules for calculating the GGI, GDI and GPS from gait data.

Examination of the distribution of the GPS follows the method of Schwartz and Rozumalski [2] in assessing concurrent validity with the FAQ, GMFCS, GGI and GDI. The FAQ is a ten-point scale rating gait function which is not specific to a particular pathology [7]. The five-level GMFCS is now the standard classification of severity of cerebral palsy [8]. The frequency distributions of the first recorded GPS score for each side of all children in each FAQ category and each GMFCS category were plotted, as were those of the reference dataset of children with no gait pathology.

A Euclidean distance such as the GPS is likely to have a chi-distribution so results are reported in terms of the median value and inter-quartile ranges (IQR). The GDI, which involves a logarithmic transformation, was found to be normally distributed by Schwartz and Rozumalski, and thus both the raw GPS and its logarithmic transform were assessed for normality using the Kolmogorov–Smirnov test.

Intra-session variability was calculated as the IQR of the GPS for each child estimated from the three trials.[1] The median of this was estimated similarly for all patients and for each category of GMFCS and FAQ.

Concurrent validity was examined by comparing the GPS against other measures of gait pathology. The GGI is the only widely accepted continuous measure of gait pathology [2]. Following Schwartz's observation that the derivation of the GGI suggests that the metric actually represents the square of the deviation from normal, the correlation between GPS and the square root of GGI ($\sqrt{\text{GGI}}$) and non-dimensional gait speed (normalised by dividing through by $\sqrt{gL}$, where L is the leg length and g is the acceleration due to gravity) were examined using Spearman's rank correlation and with GDI using exponential regression. As these correlations are essentially between two measurements made on a single gait cycle, all gait cycles (i.e. three right and three left for each child) are included. Analysis of variance (of the logarithmic transform of the GPS to ensure a normal distribution) was used to determine whether it distinguished between levels of the GMFCS and FAQ. Post hoc tests were used to identify where the differences occurred.

[1] Medians and inter-quartile ranges were estimated on the assumption that the logarithmic transform of the GPS is normally distributed. Thus the mean (m) and standard deviation (sd) of ln(GPS) were calculated and exp(m), exp($m - 0.67$sd), and exp($m + 0.67$sd) taken as estimating the median, and lower and upper quartiles of the GPS.

Table 1
Characteristics of study cohort and reference subjects. Mean and standard deviations are quoted where an assumption of normally distributed data seems reasonable, median and inter-quartile range are quoted otherwise.

	Summary statistics	Cohort	Reference
Number		407	38
Age (years)	Mean (sd)	12 (3)	11 (3)
BMI (kg/m^2)	Mean (sd)	20 (5)	19 (5)
Non-dimensional walking speed	Median (IQR)	1.1 (0.3)	1.3 (0.2)
GPS (°)	Median (IQR)	9.7 (4.9)	5.2 (1.9)
GGI (no units)	Median (IQR)	105 (164)	17 (11)
GDI (no units)	Mean (sd)	78 (13)	100 (10)

The final part of the analysis was to investigate the properties of the individual GVSs which comprise the MAP, and to determine the relationship of the individual GVS scores with each other and with the GPS. A Spearman's rank correlation was performed between each GVS and the GPS and for each pair of GVSs.

3. Results

Data from the 407 children were used. 271 had cerebral palsy, 88 had general orthopaedic conditions (such as Perthes disease, slipped upper femoral epiphysis and rotational malalignment), 43 had other neurological conditions (such as spina bifida, hereditary spastic paraplegia and acquired brain injuries) and five were idiopathic toe walkers (Table 1).

The frequency distributions of the GPS for the categories of the FAQ (levels 6–10) and GMFCS (I–III) and also for the children with no gait pathology (there were too few children in other categories for meaningful analysis) exhibit skewed distributions as expected (Fig. 2). Kolmogorov–Smirnov tests showed significant differences from a normal distribution in the raw GPS scores for all categories (all p values < 0.05) but no such evidence for any category of the log transformed data (all p values > 0.05).

For intra-session variability, the median IQR was 0.67°. Only 6% of all patients showed an IQR of greater than 2.0°.

A moderate correlation ($\rho = .79$) between GPS and $\sqrt{\text{GGI}}$ was found, suggesting that the two measures are similar (Fig. 3a). The correlation between GPS and walking speed is weak ($\rho = -.28$, Fig. 3b) suggesting that the overall effect of walking speed is only weakly reflected in the kinematics. This suggests that the GPS and speed may serve as complementary outcome measures reflecting different domains of gait quality. There is a very strong exponential correlation between GPS and GDI ($r = 0.995$, Fig. 4), confirming that the strong mathematical relationship between them. The one-way ANOVA confirmed GPS differs with both FAQ ($p < .001$) and GMFCS ($p < .001$) and post hoc tests showed differences between all levels of the FAQ and GMFCS ($p < .02$), except for between FAQ levels 7 and 8.

Table 2 shows the Spearman rank correlations of the GVSs with GPS and with each other. It can be seen that none of the GVSs correlates particularly strongly with the GPS (knee flexion shows the highest correlation, $\rho = .72$) and that none of the GVS pairs correlate particularly strongly (pelvic tilt and hip flexion showing the strongest correlation, $\rho = .66$).

4. Discussion

The GPS has strong face validity being based on the RMS difference between gait data for an individual child and the average data from children with no gait pathology. Analysis of intra-session variability suggests that it is also a reliable measure (within a single session). The moderate correlation with $\sqrt{\text{GGI}}$ and the significant differences in GPS between both FAQ and GMFCS levels provide further evidence of validity.

The extremely strong correlation between the GPS and the GDI confirms the theoretical conclusion that the two are based on essentially similar measures of difference. A consequence of this is that any evidence validating one will automatically stand as a validation of the other. Indeed, in this context this paper can be read as independently replicating the study of Schwartz and Rozumalski [2] in a different laboratory and population, and strengthening the conclusion that both the GDI and the GPS are valid and largely equivalent measures of gait pathology. Reporting of a raw score for GPS and a transformed and scaled index for GDI, however, results in them having quite different properties. The decision as to whether one or other is preferable thus rests on a consideration of these differences.

The GDI is derived from gait feature analysis which is based on a very large dataset of subjects with a wide range of gait pathologies. Schwartz and Rozumalski [2] have made their gait features publicly available so that this makes little practical difference to calculating either measure for data derived from the conventional gait model. It does, however, impose a considerable barrier to extending similar techniques to data derived from different gait models or different activities (running, stair climbing, etc.). The GPS is independent of the feature analysis and can be calculated directly from the data of an individual and the averaged data of people with no gait pathology. On the other hand, Schwartz and Rozumalski [2] have outlined several interesting properties of feature analysis and having a measure of gait pathology that derives directly from the analysis has its attractions.

Another potential advantage of the GPS is the decomposition referred to here as the MAP. The MAP provides useful insights into which variables are contributing to an elevated GPS. The lack of strong correlations of the individual GVSs with the GPS and with each other suggests that there is considerably more information contained within the MAP than in the GPS alone. There is a simple mathematical relationship between the GPS and GVSs as the GPS is the RMS average of the GVSs. Whilst it is possible to conceive of a similar decomposition of the GDI it does not have the same elegance. The extension of logarithmic transform and z-scoring to the constituent gait variables, in particular, would lead to a complex relationship between component scores and the GDI.

The other major difference between the two scores is that the GPS is defined as a raw score whereas the GDI is transformed and

Table 2
Correlations between GPS and GVS and between the different pairings of GVS expressed in terms of Spearman's rank correlations (ρ).

	Pel Tilt	Hip Flex	Knee Flex	Ank Dors	Pel Obl	Hip Abd	Pel Rot	Hip Rot	Foot Prog
GPS	.47	.63	.72	.60	.44	.44	.47	.44	.57
Pel Tilt		.66	.34	.26	.29	.24	.19	.09	.10
Hip Flex			.54	.36	.30	.26	.21	.15	.15
Knee Flex				.56	.36	.35	.34	.10	.31
Ank Dorsi					.31	.32	.31	.09	.23
Pel Obl						.61	.28	.14	.24
Hip Abd							.36	.18	.18
Pel Rot								.17	.22
Hip Rot									.12

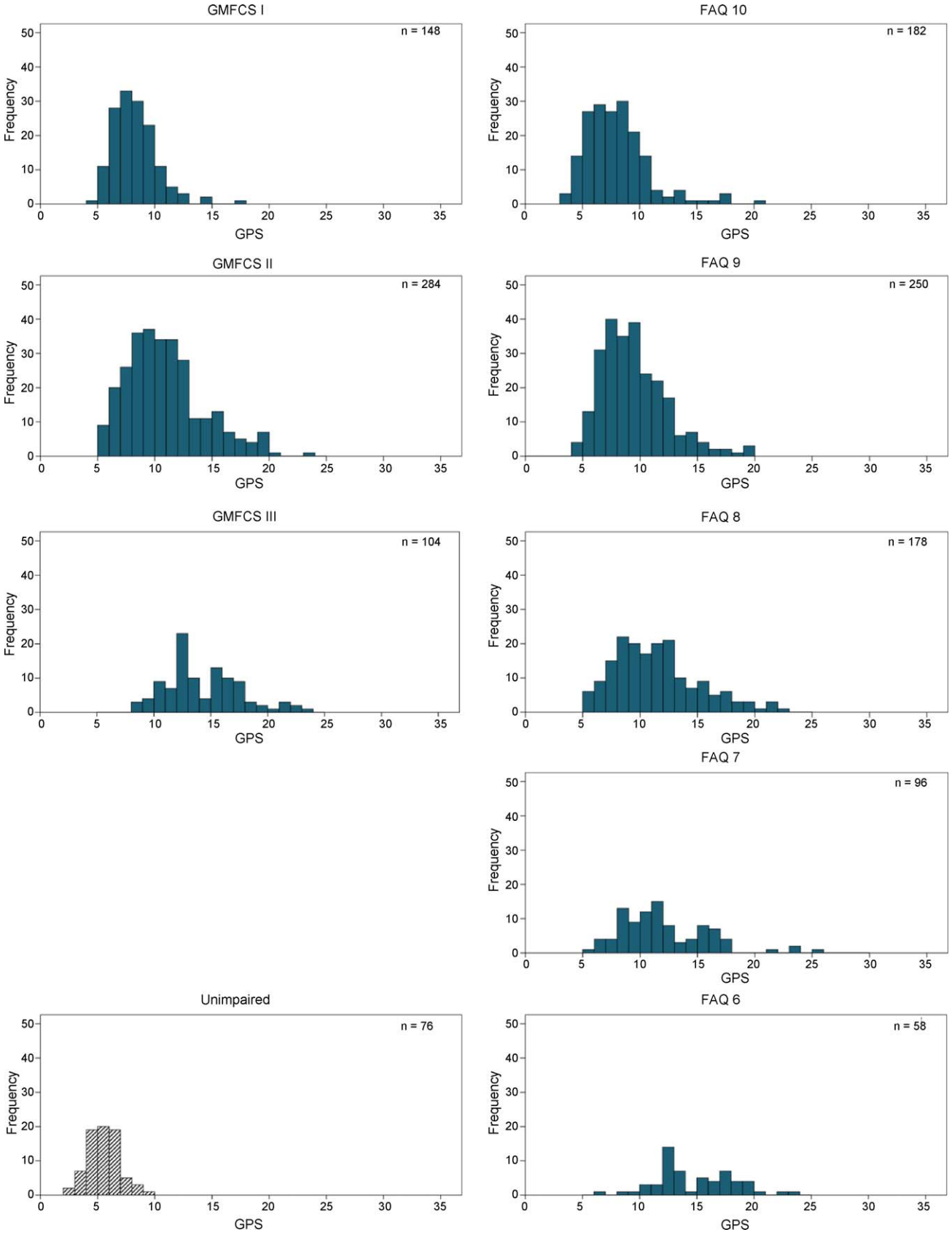

Fig. 2. Frequency distribution of the GPS across different levels of the GMFCS (left column), FAQ (right column) and from children with no gait pathology (bottom left).

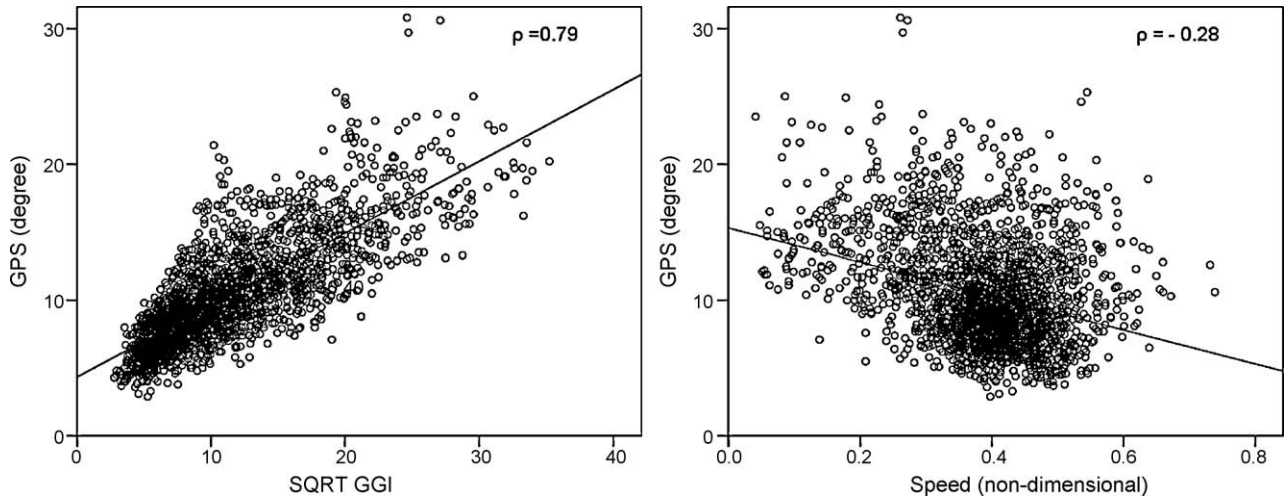

Fig. 3. Correlations of GPS with ($\sqrt{GGI}$) and non-dimensional walking speed displaying linear regression line.

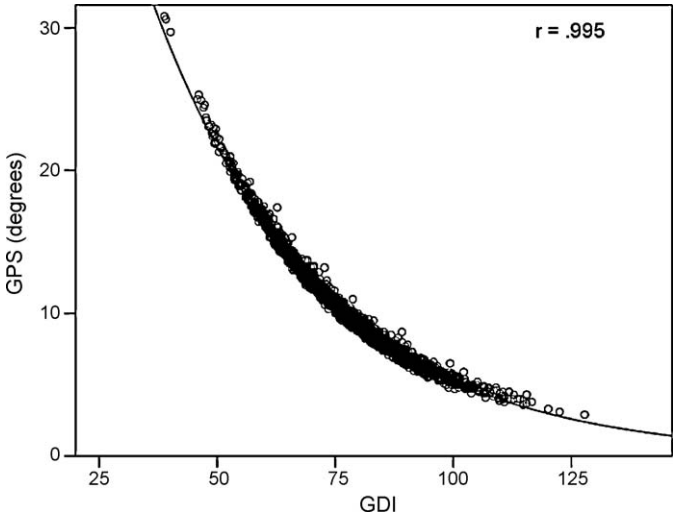

Fig. 4. Correlation of GPS with GDI displaying exponential regression line.

scaled. The GPS is reported in the same units (degrees) as the kinematic variables and its interpretation is based upon this. The interpretation of the GDI is based on the scaling which has an average score of 100 for people without gait pathology and −10 units for every standard deviation away from this. Choice of which is more appropriate may be dependent on the purpose for which such scales are being used and also on personal preference.

The logarithmic transformation used to derive the GDI results in it having better behaved statistical properties than the GPS. The normal distribution of the GDI within different categories of the FAQ does provide a basis for using parametric statistics directly. To be rigorous it makes sense to perform parametric statistics on the logarithmic transform of the GPS or non-parametric statistics on the raw scores. On the other hand the linear relationship between the GDI and difference from the average data for people with no gait pathology is lost. A person whose data is twice as different from that of people with no gait pathology than another person's will have twice the GPS.

5. Conclusion

The study concludes that GDI and GPS are alternative and closely related measures. The GDI has prior art and is particularly useful in applications arising out of feature analysis such as cluster analysis or subject matching. The GPS will be easier to calculate for new models where a large reference dataset is not available and in association with applications using the MAP.

Acknowledgements

The authors acknowledge funding support from the National Health and Medical Research Council of Australia [Centre for Clinical Research Excellence in Gait Analysis and Gait Rehabilitation Grant No 264597].

Conflict of interest

Authors Richard Baker, Jennifer L. McGinley, and Oren Tirosh have filed a patent through their employers for an invention making use of some of the ideas described in this paper. Otherwise none of the authors have any financial and personal relationships with other people or organisations that could inappropriately influence (bias) their work.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gaitpost.2009.05.020.

References

[1] Schutte LM, Narayanan U, Stout JL, Selber P, Gage JR, Schwartz MH. An index for quantifying deviations from normal gait. Gait Posture 2000;11:25–31.
[2] Schwartz MH, Rozumalski A. The gait deviation index: a new comprehensive index of gait pathology. Gait Posture 2008;28:351–7.
[3] Tulchin K, Campbell S, Browne R. Proceed with caution: large number of controls are needed for and accurate Gillette Gait Index. In: 13th Annual Meeting of the Gait and Clinical Movement Analysis Society; 2008.
[4] McMulkin ML, Macwilliams BA. Intersite variations of the Gillette Gait Index. Gait Posture 2008;28:483–7.
[5] Schwartz M, McWilliams B, McMulkin ML, Wren T. A multi-centre evaluation of two comprehensive gait pathology indices using clinical samples. In: 13th Annual Meeting of the Gait and Clinical Movement Analysis Society; 2008.
[6] Rozumalski A, Schwartz M. Natural crouch gait classification in relation to clinical parameters. Gait Posture 2008;28S:S1–47.
[7] Novacheck TF, Stout JL, Tervo R. Reliability and validity of the Gillette Functional Assessment Questionnaire as an outcome measure in children with walking disabilities. J Pediatr Orthop 2000;20:75–81.
[8] Palisano R, Rosenbaum P, Walter S, Russell D, Wood E, Galuppi B. Development and reliability of a system to classify gross motor function in children with cerebral palsy. Dev Med Child Neurol 1997;39:214–23.